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# A Comparative Study on the Exterior Qualities of Blue Brick in Traditional Residences Based on Material Testing

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**Abstract**

Jinxi County in Jiangxi Province and Yangxin County in Hubei Province enjoy similar physical geographic conditions, and boast existing traditional residences that primarily date back to the Qing Dynasty. Moreover, the structures' external wall material primarily uses blue brick. However, the exterior quality of the blue brick used for traditional residences in both areas have distinct differences. By conducting electronic micro-analysis and x-ray diffraction analysis testing of samples of blue brick from both sites, comparative analysis of the differences in the blue bricks' elemental composition and microstructure was carried out. The results showed that the samples have differences in fusion degree of the microstructure of crystalline grain, uniformity degree of the distribution of various element content, and contents of $TiO_2$ and Ca0, leading discrepancies in the degree of smoothness of the surface, the uniformity of color, and the variation in color of the blue brick.

**Keywords:** electronic micro-analysis, X-ray diffraction, traditional residences, blue brick, exterior quality

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## INTRODUCTION

Jinxi County in Jiangxi Province and Yangxin County in Hubei Province are both located along the middle and lower reaches of the Yangtze River. Jinxi County is located in the east of Jiangxi Province and Yangxin County is located in the southeast of Hubei Province. Both areas are typical examples of a subtropical humid monsoon climate. The climates in both areas are similar, with hot summers, cold winters and high humidity; moreover, they are both hilly areas with similar geographical conditions. The architecture in both areas is typical of that found in Southeast China and boasts a rich amount of traditional residential architecture that is representative of the traditional architectural styles and skill levels in both areas. The majority of existing residences are Sishuiguitang (square houses with an inner courtyard open to the sky where rain water drains off, typical of the architecture around the Yangtze River delta) in the "Tianjing" (courtyard) style of architectural shape and structure. They are built in a masonry-timber structure, with internal timber frames taking the weight and an external wall comprised of bricks (Huang 2008, Li and Li 2006).

Via onsite surveys of the traditional residences in Jinxi County and those in Yangxin County, this paper discovered that the blue brick used on external walls in Jinxi County had smooth surfaces and the color was uniform and tended to be white; whereas those used in Yangxin County had rough surfaces with a mottled color that tended to be yellow (**Fig. 1**). The shape and structure of both forms of architecture were similar, while the color, texture and other elements of the outer wall blue bricks had clear differences in exterior quality characteristics. Apart from the influence of masonry techniques, the influence of the internal factors of the blue bricks themselves is also extremely worthy of research and investigation.

Because the materials, firing processes, length of use and environments differ, the blue bricks used in traditional residences also have different qualities. The bricks in these residences will suffer from erosive effects from the surrounding environment during use, and as the materials used in the bricks themselves also differ, this will give them a different texture when exposed to external influences. There are many different kinds of mineral elements contained in the raw materials in blue bricks when they are fired. The form the iron oxides

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**Fig. 1.** Appearance of Blue Brick

take after being fired is the main factor dictating the color of the brick; however, the content and degree of uniformity of metallic oxides in the brick also affect the color and uniformity of the color (Zhu 2015). There is relatively few research that studies the blue bricks of traditional Chinese residences, and most domestic research places emphasis on the qualitative analysis of aesthetics of the materials used in bricks in traditional residences (Li 2013). Although some testing experiments have been carried out on the brick materials used in traditional residences (Cao and Cao 2014, Jie 2014, Li et al. 2014a, Li et al. 2014b), there is still a lack of testing that directly focuses on research into the exterior qualities of blue brick, as well as correlation analysis of test results on the exterior qualities and materials in blue brick.

In order to assess the effect of the elemental composition and microstructure of blue bricks on the bricks' exterior qualities in traditional residences in Jinxi County and Yangxin County, this paper conducted scanning electron microscope (combination of SEM and EDS) and X-ray power diffraction (combination of XRD and XRF) testing on the blue bricks used in outer walls of traditional residences at both locations to gain comparative analysis of the differences in elemental composition and microstructure, as well as the different effects on brick quality, and thus conduct a more scientific and accurate research on this subject.

## SAMPLE SELECTION AND TESTING PROCESS

### Sample Selection

While selecting samples for testing, according to the unique variable principle one should select brick materials from the same time period, the same location and the same external environment. After much deliberation the blue brickwork on the outside walls at Li House in Xiali Village, Jinxi County, and Li House in Kanjiatang Village, Yangxin County, were selected for the subjects of testing. According to genealogical records, the Li House in Xiali Village and Li House in Kanjiatang Village were both constructed in the Qing Dynasty and have been used as residences for almost the same period of time; moreover, Jinxi County and Yangxin County are both located in the middle and lower reaches of the Yangtze River, with similar climatic conditions and the blue bricks are in similar environments. The blue brickwork selected as the test objects on the middle sections of the outer walls at the two selected sites boast intact surfaces, no distortion, no cracks and no microbial erosion, guaranteeing that test results are representative.

### Testing Process

#### *Electronic micro-analysis*

Two brick samples of blue brick were taken from the sites at Jinxi County and Yangxin County and sanded down, with the impurities removed. Using a cutting machine, multiple fragments were cut from the center of each brick sample. Of these fragments, one from each brick sample was taken as a test sample and electron microscope analysis was conducted after the sample had been sprayed in a conductive coating. The specific testing method was conducted according to the General Rules for Measurement of Length In Micron Scale by SEM(GB/T16594—1996, GB/T16594—2008), with a scanning electron microscope (SEM) used to conduct analysis on the appearance and structure of the blue brick samples' surface and produce SEM pictures in 500, 2500, 5000 and 10000 magnifications.

The top left, bottom left, top right, bottom right and center of each of the two selected brick samples underwent x-ray energy dispersive spectrometer (EDS) electron beam (probe) testing. The specific testing method was conducted according to the Instrumental Specification for Energy Dispersive X-ray Spectrometers with Semiconductor Detectors (GB/T

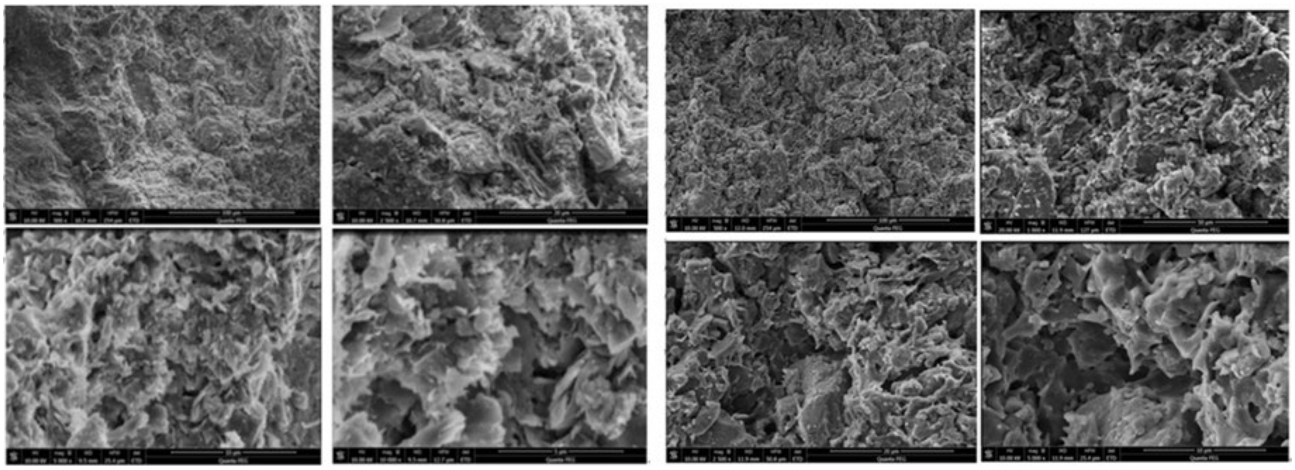


**Fig. 2.** SEM Pictures of Blue Brick

20726-2006), to gain quantitative determination on the different types of elements and content within the micrometer scale volume, with the results displayed on an atomic percentage and producing an EDS energy spectrum for each of the micro regions from the brick samples.

### *X-ray diffraction analysis*

After the above testing was complete, the two brick samples were crushed into powder and x-ray diffraction (XRD) testing conducted on the samples once they had passed through a 200 μm mesh. The specific testing method was conducted according to the Phase Quantitative Analysis of Silica Bricks X-ray Diffraction Method (YB/T 172-2000), which allowed the determination of the brick samples' mineral composition and produced XRD pictures for the samples from each site.

After X-ray diffraction analysis, an XRF (X-ray Fluorescence) tester was used to test the powder from the brick samples. The specific testing method was conducted according to the XRF Machine Operation Flowchart, to determine and gain quantitative analysis of the interior elements of the brick samples, with the results shown in quality percentage to gain an XRF element table for each of the brick samples.

## TEST RESULTS

A scanning electron microscope can provide relatively visual microstructural information, with various different genetic types of brick material displaying different crystalline structure under the microscope. The strength of dry mud brick was very low and some minerals turn to liquid as they are melted under the high temperatures during firing, which gives a fusing effect within the brick, fusing dispersed mineral particles that helps reduce the air gaps within the brick. This helps complete the overall structure, increasing the strength of the brick. By analyzing the brick samples' microstructure, a clear idea of the merits and disadvantages of blue brick mechanical properties can be gained. **Fig. 2** are SEM pictures of the blue brick fragments taken from the outer walls at Jinxi County's Xiali Village Li House and Yangxin County's Kanjiatang Village Li House. From the pictures, it is clear that the surface topography of the blue bricks at both sites have significant differences. The borders of the crystalline grain from the blue brick samples taken from Jinxi County's Xiali Village Li House (hereafter referred to as the Jinxi County brick sample) have formed a smooth and blurry state, with a more full and curved appearance, while the vitreous quality fills in the majority of air gaps, the air holes on the surface of the crystalline grain are better closed, and the fusion between the minerals micro particles are very distinct. The borders of the crystalline grain from Yangxin County's Kanjiatang Village Li House sample (hereafter referred to as Yangxin County brick sample) are clearly layered, with more distinct edges and corners, a more broken structure, with larger air gaps between crystalline grains and more air holes on the surface. Via these comparisons it is clear that the Jinxi County brick sample has a more compact fusion in its crystalline grain microstructure and better mechanical properties than the Yangxin County brick sample.

The EDS energy spectrum shows the various types of elements and content within the micrometer scale. By comparing the change of the same types of elements and content within different micro regions, one can analyze the uniformity of distribution of these

**Table 1.** EDS Energy Spectrum

| Jinxi Blue Brick | 1 (upleft) atom % | 2 (left lower) atom % | 3 (center) atom % | 4 (upper right) atom % | 5 (low right) atom % | Yangxin Blue Brick | 1 (upleft) atom % | 2 (left lower) atom % | 3 (center) atom % | 4 (upper right) atom % | 5 (low right) atom % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| O K | 66.27 | 68.23 | 64.92 | 61.93 | 66.24 | O K | 62.93 | 45.07 | 51.42 | 63.38 | 58.23 |
| MgK | 1.07 | 0.49 | 0.89 | 0.58 | 1.03 | MgK | 0.20 | 0.00 | 0.05 | 0.84 | 0.53 |
| AlK | 13.37 | 5.61 | 11.92 | 7.07 | 11.65 | AlK | 2.58 | 12.35 | 3.66 | 5.35 | 8.12 |
| SiK | 13.18 | 21.05 | 17.50 | 26.06 | 14.41 | SiK | 29.24 | 29.53 | 40.40 | 23.87 | 28.44 |
| K K | 0.75 | 0.30 | 0.62 | 0.41 | 0.59 | K K | 0.20 | 2.37 | 0.42 | 0.51 | 1.29 |
| CaK | 0.08 | 0.04 | 0.04 | 0.07 | 0.07 | CaK | 0.22 | 0.54 | 0.13 | 0.18 | 0.45 |
| FeK | 1.96 | 0.67 | 1.00 | 0.87 | 1.08 | FeK | 0.28 | 7.07 | 0.68 | 0.69 | 2.09 |
| TIL | 0.05 | 0.04 | 0.07 | 0.06 | 0.06 | TIL | - | - | - | - | - |

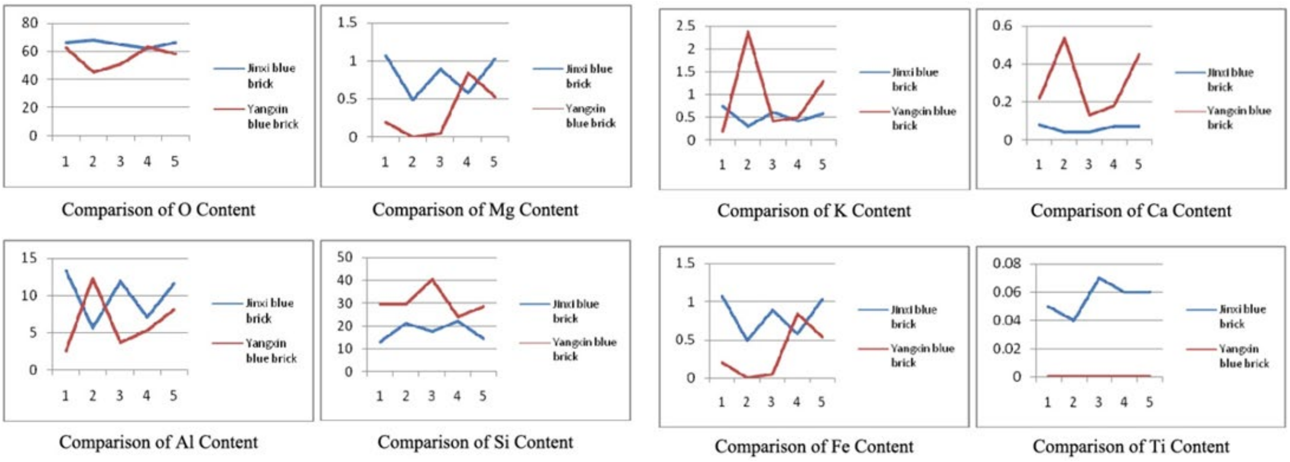


**Fig. 3.** Comparison of Elemental Content

elements. **Table 1** shows the EDS energy spectrum from the five different locations, upper left (point 1), lower left (point 2), middle (point 3), upper right (point 4) and lower right (point 5), taken of the Jinxi County and Yangxin County samples. From the table, it is clear that there are distinct differences in the elemental composition and content of both brick samples. To get a better visual reflection on the fluctuation of the elemental content in the different locations, a comparative graph (**Fig. 3**) of the content changes of various elements in different micro regions was drawn up based on the EDS energy spectrum. From the pictures, it is clear that the atomic percentage of fluctuation of the same types of elements in different micro regions of the Yangxin County brick sample is much higher than the Jinxi County brick sample. Via an analysis of the primary elements, it is clear that the range of change in the O, Mg, Al, Si, K, Ca and Fe of the elemental content in different micro regions of the Jinxi County brick sample was 6.30%, 0.58%, 7.96%, 12.88%, 0.45%, 0.04% and 1.29% respectively; and that the range of change in the O, Mg, Al, Si, K, Ca and Fe elemental content in different micro regions of the Yangxin County brick sample was 18.31%, 0.84%, 9.77%, 16.53%, 2.17%, 0.41% and 6.79% respectively. The range of change of Ti elemental content in different micro regions in the Jinxi County brick sample was 0.03%, with almost none found in the Yangxin County brick sample. The above analysis allows one to determine that there were comparatively smaller change ranges in the same types of elements in different micro regions in the Jinxi County brick sample, which shows that various elements within the Jinxi brick sample are more evenly distributed, and those in the Yangxin County sample less evenly distributed.

The XRD pictures show that when the x-ray passed through the brick samples inner crystalline body, there was an overlay of diffracted waves, producing an analysis of the diffraction pattern on the photographic plate and allowing one to know the mineral composition of the brick samples. From the XRD pictures (**Fig. 4**) of the Jinxi County and Yangxin County samples it is clear that the diffraction curves of both samples are similar, showing that mineral compositions of each sample are similar, with the dominant elements consisting of Si02 and dickite. After that a XRF tester was used to test the powder from either sample, producing an XRF element table of each of the samples of brick powder that shows the primary elements and quality ratio within the brick samples. From the **Table 2**, it is clear that there is a difference in the primary elemental content of blue brick from either site, with the element quality ratio of O, Si, Mg and K from the Jinxi County sample 0.48, 4.69, 0.13 and 0.31 respectively for a cardinal number of the elements accounting for 0.9%, 12.1%, 44.8% and 24.2% respectively. The element quality ratio of Al and Fe in

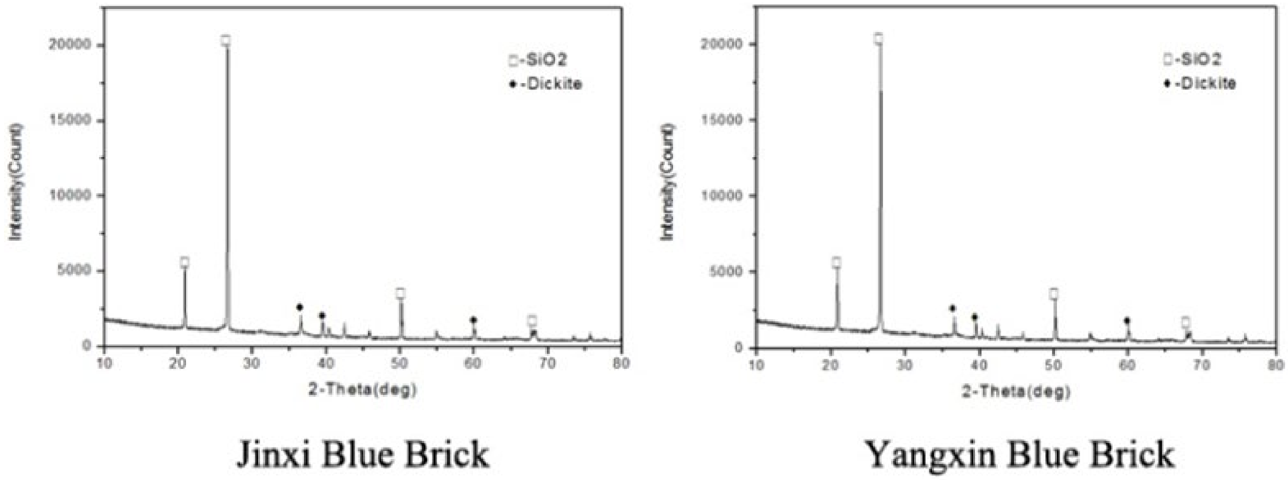


**Fig. 4.** XRD Picture of the Blue Brick Samples

**Table 2.** XRF Element Table of the Blue Brick Samples

| Jinxi Blue Brick | | | | | | |
|---|---|---|---|---|---|---|
| O | Si | Al | Mg | Fe | K | Ti |
| 49.56 | 31.15 | 12.48 | 0.29 | 4.21 | 1.28 | 0.51 |

| Yangxin Blue Brick | | | | | | |
|---|---|---|---|---|---|---|
| O | Si | Al | Mg | Fe | K | Ca |
| 50.04 | 35.84 | 7.11 | 0.42 | 3.58 | 1.59 | 0.34 |

the Jinxi County brick sample is higher than that of the Yangxin brick sample by 5.37 and 0.63 respectively, with a cardinal number of the elements accounting for 43% and 15% respectively. The elemental content of Al in the Jinxi County brick sample was clearly higher than that of the Yangxin County brick sample, while the elemental content of Mg was clearly lower, the elemental content of O was similar, with the elemental content of FE slightly higher and that of Si and K slightly lower. There were also differences in the types of primary elements in the blue brick from either site. Elements in the Jinxi County brick sample consisted primarily of O, Si, Al, Mg, Fe, K and Ti, with very little Ca; whereas the elements in the primary elements in the Yangxin County brick sample were O, Si, Al, Mg, Fe, K and Ca, with almost no Ti.

## ANALYSIS AND DISCUSSION

Via a comparative analysis of the tests conducted on the Jinxi County and Yangxin County brick samples, the following will conduct a discussion of the relationship between the blue brick material test experiment results and the exterior quality of the blue bricks from the three angles of the blue brick micro structure's fusion intensity and the smoothness of its surface, the content uniformity of the elements in the blue brick, and the types of primary elements and colors of the blue brick.

From an analysis of the SEM pictures from the brick samples at both sites, it is clear that the Jinxi County blue brick's microstructure was more complete, and the structural density and the degree of layer integration were better than in the blue brick from the Yangxin County site; the fluidity of the vitreous quality helped to connect the crystalline grains, with capillary force and surface tension acting to fill some of the air gaps, forming the primary framework for load-carrying capacity, and showing better mechanical properties (Zhu 2009). Jinxi County and Yangxin County are both located in subtropical monsoon climates, with high temperatures and rainfall in summer, moderate temperatures and rain in winter and an overall climate characterized by hot summers and cold winters. There is a relatively large difference in monthly average rainfall and annual temperatures at both sites. After years of experiencing the repeated annual shift from moist to dry, the better fused microstructure of the Jinxi County blue brick allowed it to maintain a comparatively smooth surface, whereas the surface of the Yangxin blue brick that contained more air gaps in its microstructure had relatively worse surface properties, making it easily porous, causing the surface to powder, and becoming coarse with many gaps.

Via an analysis of the comparison chart of the content change in the various elements in different micro regions of the brick samples from both sites, it is clear that the fluctuating margins of the various

**Table 3.** Correlation Analysis of Material Testing and Exterior Quality

| | Crystalline Grain Fusion | Surface Smoothness | Element Distribution | Color Uniformity | Differing Components | Color Trends |
|---|---|---|---|---|---|---|
| Jinxi County | Better | Smooth | More Uniform | Uniform | $TiO_2$ | White |
| Yangxin County | Worse | Coarse | Less Uniform | Mottled | CaO | Yellow |

elements in different micro regions in the Jinxi County brick sample were lower than those in the Yangxin brick sample, showing that the various elements in the Jinxi County brick sample were more uniformly distributed than those in the Yangxin County brick sample. This distribution of elements represents the influence the distribution of chemical composition had on the colors of the blue brick, with a uniform distribution of elements inevitably leading to a uniform coloring of the blue brick, and an uneven distribution of elements having the opposite effect (Zhang 2003). Based on the above analysis, the preliminary conclusion can be reached that the various elements in the Jinxi County blue brick were more uniformly distributed, leading to a more uniform coloring of the brick; whereas the various elements in the Yangxin County blue brick were less uniformly distributed, leading to a more mottled coloring of the brick. However, due to the difficulty in gaining accurate positioning of the testing points in the energy spectrum analysis, this conclusion can only be taken as a reference in the investigation into the degree of uniformity of blue brick's color (Fan 2000).

The XRD pictures of the brick samples from both sites are similar, showing that the primary mineral composition in both brick samples were $Si0_2$ and dickite. Further comparative analysis of the types and content of primary elements in the brick samples from both sites can be conducted via the XRF element tables. The iron oxides in fired clay blue bricks primarily formed Fe0 and $Fe_30_4$, this gave the bricks a dark blue color and is the primary factor in determining the dark blue color of clay bricks (Liu 2015); however, other metal oxides will also play a role in determining the color of the bricks. From the XRF element tables from both sites, it is clear that there are distinct differences in the content of the metallic elements Al, Mg, Ca and Ti in the brick samples from Jinxi County and Yangxin County. A look at research into the influence of Al and Mg oxides on clay bricks shows no clear references to whether these oxides have an influence or the extent of that influence on the color of blue bricks (Xie and Ye 2010, Miu and Lin 2007). Therefore this paper will not discuss the influence these two elements had on this experiment at this stage, and awaits a following stage of more in depth research. However, from relevant research into factors affecting the color of bricks (Zhu 2005), it is clear that if the clay contains calcium carbonate (primarily composed of $CaC0_3$), after the bricks are fired, the Ca0 will cause a slight yellow or brown hue. Moreover, $Ti0_2$ is a very precious "white pigment" in the natural world, with an optimal white color; and thus clay containing $Ti0_2$ produces a light tone of blue bricks (Du 2016). The XRF chart shows that the Jinxi County brick samples contained more of the element Ti and less of the element Ca; whereas there was more of the element Ca in the primary elements of the Yangxin brick sample and basically none of the element Ti. From this, it is clear that there is a certain amount of $Ti0_2$ in Jinxi County blue brick and less Ca0; whereas in Yangxin County blue brick there is a certain amount of Ca0 and basically no $Ti0_2$ (Shi 2005). Thus, one can conjecture that apart from the influence the existence of Fe in the firing process has on the color of the blue bricks at both sites, the differing content of Ca and Ti in the clay at both sites is also an influencing factor on the different color trends at both sites.

## CONCLUSION

Via a correlation analysis of the test results and blue brick quality of the brick samples from both sites, this paper discovered that the state of crystalline grain fusion and compactness of the microstructure fusion in the Jinxi County brick sample was better than that in the Yangxin County brick sample, meaning that Jinxi County blue brick is still able to maintain a relatively smooth surface over years of repeated annual shifts from moist to dry climate, whereas Yangxin County blue brick has a coarse and porous surface. The more uniform distribution of various elements within the brick material in Jinxi County blue brick gives the brick a more uniform coloring than Yangxin County blue brick, which has relatively mottled coloring. Apart from the influence the presence of the element Fe forms during the firing process on the color of the blue brick at both sites, the content of white coloring $Ti0_2$ and relative lack of Ca0 in Jinxi County blue brick, and the certain amount of Ca0 and basic nonexistence of $Ti0_2$ in Yangxin County blue brick are influencing factors in the white trend of Jinxi County brick and the yellow trend of Yangxin County brick (**Table 3**).

This research conducted material testing of blue brick samples from two different regions to draw comparative analysis on the differences in element composition and microstructure found in the brick from both sites, and conducted correlation analysis between these differences and the exterior quality of the blue brick from each region, in an attempt to determine the effects elemental composition, microstructure and other inherent properties of the blue brick had on the exterior quality of the architecture. These findings are helpful for further research into the craftsmanship of blue brick in different regions, scientific quantitative explanations of the influence architectural materials have on the appearance of architectural craftsmanship, and offer scientific instruction into undertaking accurate restoration and repair of ancient architecture.

## ACKNOWLEDGEMENT

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